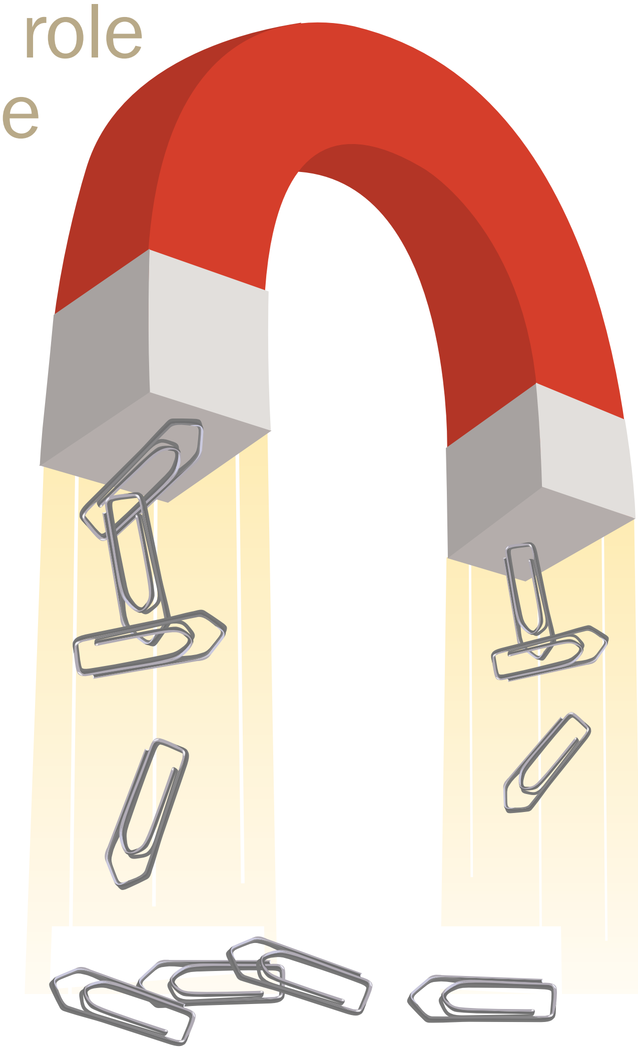
Using metacognition to develop understanding of the role of evidence in science

by Erin Peters Burton



One of the most prominent reforms in science education is inquiry science (AAAS 1993; NRC 1996). Educators who teach inquiry science strive to have students think scientifically and understand the nature of science. Because of barriers such as limited time and limited access to scientists, teachers sometimes have difficulty teaching how science operates as a discipline (Hogan and Maglienti 2001) and revert to teaching science as a collection of facts. Students have a difficult time understanding the rationale for being precise and detailed, as is necessary in science. This article focuses on strategies to encourage students to make more effective observations, collections, and recordings of data. The strategies consist of a metacognitive intervention that is efficient, compact, and research based, and designed to be placed into established content curricula to encourage students to think scientifically about the role of valid evidence. The techniques presented in this article demonstrate how to encourage students to be more thoughtful, intentional, and careful when recording data that will eventually support or refute their original claim.

Teaching the nature of science is important in producing scientifically literate students because students who have an understanding of the nature of science have a robust conceptual framework that helps to connect discrete facts into larger, thematic conceptual knowledge traditionally taught in science (Duschl 1990; McComas, Almazroa, and Clough 1998). The nature of science can be considered the inherent guidelines that drive the scientific discipline and consists of seven interconnected ideas (Lederman 1992):

1. Empirical evidence is used in making claims.
2. Scientists engage habits of mind to create valid information.
3. Scientific ideas are dependent on social and historical factors.
4. Science and technology are dependent on each other.
5. Scientific knowledge is mostly stable, but can change because of new ideas and technologies.
6. Science is a creative endeavor.
7. Laws and theories play different roles in knowledge generation.

FIGURE 1 MPI–S for teaching the role of empirical evidence in making claims in science

Phase	Prompt
Phase 1: Modeling	(Example of observations that a scientist makes when conducting an investigation on properties of static electricity) • When an inflated balloon rubbed 30 times with wool is brought 1 cm away from paper ripped into 1 cm × 1 cm pieces, the paper is attracted to the balloon. • When the same balloon rubbed 30 times with wool is brought 1 cm away from tin foil ripped into 1 × 1 cm pieces, the tin foil is not attracted to the balloon. • When the same balloon rubbed 30 times with wool is brought 1 cm away from 1 cm × 1 cm Styrofoam pieces, the Styrofoam is attracted to the balloon. • Based on these three trials, balloons rubbed with wool attract nonmetal objects and do not attract metal objects.
Phase 2: Checklist	☐ My observations describe what I see, hear, or touch. ☐ My observations are made up of measurements that other people can agree upon when possible. For example, instead of saying, "It is big," I say, "The blue car is 20 cm long." ☐ My observations are clear to other people who are not performing this lab. ☐ My observations come only from my five senses and are not inferences. ☐ My observations can be used later to make inferences or conclusions. ☐ My observations are not judgments about what I thought would happen before I did the investigation.
Phase 3: Self-regulation	• Other people can understand my observation out of context. (Explain.) • My observation is free of any judgment. (Justify your answer.) • My observations are relevant to the purpose of the investigation. (How so?)

The metacognitive strategies described in this article focus mainly on the role of empirical evidence in making claims and implementation of habits of mind of scientists in student work. By using strategies to promote metacognition about the nature of science, students can evaluate their thinking to determine if it aligns with the rigorous requirements of science while still addressing content knowledge. Used strategically, metacognitive prompting will not add another topic to be addressed in an already overpacked curriculum, but will enhance content learning in addition to building views of the nature of science and content (Peters and Kitsantas 2010; Peters 2009b). Students who have an understanding of the role of evidence in their own conclusions can begin understanding how valid scientific knowledge is generated.

Metacognitive Prompting Intervention–Science

Metacognition is the ability to think about and evaluate your own thinking processes (Brown 1987), and students who are metacognitive are active participants in their own learning process (Zimmerman 2000). Using metacognition about the nature of science can result in students performing inquiry activities, then thinking about why they are conducting scientific process-

es, and evaluating their thinking compared to the way a scientist might think about the processes and outcomes. Metacognitive prompts built from identified aspects of the nature of science (McComas, Almazroa, and Clough 1998) are a concrete way to scaffold how science works to students who are underexposed to this type of thinking. Actively prompting students to evaluate their scientific thinking brings them closer to authentic scientific inquiry.

Metacognitive Prompting Intervention–Science (MPI–S) (Peters 2009a) is a strategy that has been designed for middle school students and can be embedded into existing curricula. MPI–S is developed through three phases: modeling, checklists, and self-regulation (Figure 1). In the first phase, modeling, students observe how a task in science is accomplished from a proficient model. A teacher can ask students to observe modeling of detailed, replicable observations a scientist would make in the laboratory. The checklist phase is an imitation of the model to the best of the student's ability. Given a similar task to perform as the modeling phase, students in this phase try to perform

FIGURE 2 MPI–S for teaching habits of minds in science

Phase	Prompt
Phase 1: Modeling	(Example of modeling the degree of detail and replicability for observations in making a magnet) Other people can agree that your observations, inferences, and ideas are accurate if they can redo your investigation and find similar observations, inferences, and ideas. Scientific knowledge grows when a new idea can be confirmed by the scientific community. I would want to explain things in great detail, so other people could understand my exploration. First, I would explain the shape of each magnet I used and how it was oriented before I begin. Then I would measure how far apart the magnets were when the interaction happened. Magnet #1 started to move away from magnet #2 when I brought magnet #2 closer. This started to happen when the magnets were 1 cm away from each other, and continued with a stronger force as they got closer than 1 cm.
Phase 2: Checklist	☐ I would be able to understand my data table weeks or months from now. ☐ I paid attention to all possible observations. ☐ I didn't intentionally ignore any observations because they didn't support my ideas. ☐ My data are not written haphazardly and are organized to show the main points of my investigation. ☐ I thought about different ways to organize my data and decided on the one that best emphasizes my conclusion.
Phase 3: Self-regulation	• Are your data organized to clearly illustrate your point? Give evidence to explain how you know this. • Have you ignored any factors in taking the data? How have you checked your work to consider all factors in taking the data? • How might other readers who have not participated in this investigation make sense of your data?

the task on their own for the first time with support from a checklist of skills. For example, students can make their own observations, and then use a checklist to make sure they thought in a similar way to a scientist, and the teacher can give feedback on the level of detail of the observation. After students write an observation, they can be presented with a short checklist of the factors a scientist would consider in making the description of the observation, such as the following:

1. The observation can be reproduced by another person.
2. The observation does not use judgmental language, such as "This is good, bad, ugly…"
3. The observation has qualities that use a standard measuring system, instead of a relative comment such as "big" or "small," when possible.
4. The observation is descriptive and has no pronouns such as "it."
5. The observation made in my notes could be understood months or years from now.

The self-regulation phase occurs after several attempts at making observations, and students have the skills to explain their thinking in terms of a scientific way of knowing on their own. The ability to self-regulate the nature of science is assessed by the questions found in Figures 1 and 2. Students who progress through all phases of the model should be able to think about and evaluate their ideas according to a scientific way of knowing. MPI–S is useful because it provides concrete coaching to students so they can be more proficient in thinking about their own thinking. When students are capable of articulating the comparison of their processes and knowledge to those embraced by scientists, they have completed the self-regulation phase.

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Figures 1 and 2 provide examples of models, checklists, and questions for all three phases of the intervention. This intervention is intended to be iterative, and students need to try to answer the questions or consider the items in the checklist several times in order to master and think more deeply about their own thinking. The models are only examples, and should be adapted to the specific task the student is trying to master.

MPI–S is intended to be placed strategically into already constructed content curricula, such as a guided inquiry lab. The following provides an example of how to embed the phases into a series of investigations.

Examples of MPS–I

In a guided investigation about the behaviors of permanent and temporary magnets, phase 1, modeling, would consist of the teacher determining the location of the strongest magnetic force, the poles, on oddly shaped magnets by observing their attraction and repulsion behavior and explicitly recording observations in front of the class that a scientist would consider valid. Modeling for this example would be similar to the modeling example given in Figure 2. The teacher should be sure that students found the statements intelligible before moving to the next phase.

Once they are familiar with the model, students would be asked to perform a similar task as the model and would be given the support of the checklist from phase 2 (checklists) to explicitly monitor their work. In this example, students in small groups would be given a demonstration of how to magnetize a piece of iron with a permanent magnet. Following the demonstration, students are challenged to try to maximize the magnetic strength of the iron. Students would be expected to design a simple procedure and record their observations, which they would then share with the class. The similar task in this case is providing empirical observations about the strength of magnetic attraction with the metal, but the observations must now be made in a different context from the permanent magnet context, which is the context of creating a magnet. Transferring the context of the phenomenon from behavior of permanent magnets to creating a magnet is the challenge for this phase. Students performing phase 2 would be expected to read the checklist and check off the item if they accomplished it. If students did not accomplish the item, they would be instructed by the teacher to go back and redo the task to incorporate the item on the checklist. As the groups discuss the level of

detail of observations and validity of the statements as prompted by the checklist, the teacher should circulate around the classroom to continue to support students. In order to monitor students' performance in making observations, the teacher would ask the class to check to see if they understand what the group did and how they describe the strength of magnetization of the iron (by picking up staples, for example).

Finally, the ability to make empirical observations or have good habits of mind of a scientist would be developed to a more sophisticated level in phase 3, self-regulation, when students were able to answer more advanced questions, such as thinking about their rationale for choosing particular evidence in making claims. This portion of the prompts consists of questions placed at the end of the series of investigations so that students could reflect on the combination of activities. For example, using questions from either Figure 1 or 2, groups of students could evaluate the level of detail and ability to replicate each other's answers the next day in class, and the teacher would facilitate a discussion of their answers. If students could justify how they decided the validity of evidence for their claim, then they could successfully be metacognitive about these aspects of the nature of science.

Benefits of MPI–S

Education research using an experimental design has been conducted and has demonstrated the effectiveness of MPI–S in developing both nature-of-science knowledge and content knowledge (Peters 2009a). A partial example can be seen in Figure 3 (available in the online version of this article; see *www.nsta.org/middleschool*). In this research, a comparison group performed a guided inquiry without the prompts, and an experimental group performed the same inquiry with the prompts. Students in the experimental group had significantly higher scores on their knowledge of the nature of science and on content knowledge in pre- and posttests (Peters and Kitsantas 2010). This research, conducted on almost 200 eighth-grade students, has shown that students who have used MPI–S over an eight-week period outperformed students in a comparison group in both nature-of-science knowledge and in content knowledge, even though MPI–S is not content based (Peters and Kitsantas 2010; Peters 2009b). When asked to record the number of prompts used in their thinking (even when not provided in writing), students reported that they continued to remember the prompts from their first unit at the end of the intervention (Peters and Kitsantas 2010; Peters 2009b). A student who has used MPI–S illustrates this gain in metacognition by stating, "When I first started the prompts, I would go back to change my answer to make it more detailed. At about the third set of prompts, I would remember the checklists, and I didn't have to change my answer much."

However, some students needed several iterations of the checklists and questions to understand how to make scientifically valid observations, collections, and recordings of data. Even students who initially struggled with MPI–S eventually saw the benefit of adopting the habits of mind of scientists. An example is a student who originally responded to the clarity of a data table with the statement "I know it is right because I am smart." Eventually this student began answering questions about cognition more thoughtfully: By the third time he had experienced MPI–S embedded in inquiry lessons, this same student, when asked how he knew his data table was clear to other people not involved in the activity, answered, "I asked a friend who is not in my class to tell me what it [his data table and conclusions] meant, and he got it right." This student was embracing the practices of peer review and habits of mind of scientists by independently seeking confirmation of his clarity from a student outside of the class.

Actively prompting students during inquiry helped to guide their thinking and got them to begin thinking about their own cognition. This is a giant step toward creating independent, lifelong learners who are scientifically literate. ■

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